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14 Molar Concentrations of Alkali-Activated Geopolymer Concrete

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Abstract. The increase in construction activities due to economic and population growth has led to the higher demand and utilization of cement. But cement production leads to the pollution of the environment. Consequently, this study examines the utilization of both ground granulated blast furnace slag (GGBFS) and corncob ash (CCA) as source materials in the production of geopolymer concrete (GPC). GGBFS was replaced by CCA in 0%, 20%, 40%, 60%, 80% and 100% respectively using Grade 30 (M30) mix design proportion. Alkaline liquids were prepared to obtain 14 molar concentrations and used to activate the source materials. Slump, density and compressive strength of GPC were determined and compared with Portland cement concrete (PCC). The research findings indicate that GPC has higher compressive strength than PCC. Based on the relationship between the compressive strength and the density, a model equation is established. And the equation is used to predict the compressive strength of GPC with respect to the density. Reprocessing of CCA and GBFS as emerging low-carbon footprints appears to be a feasible solution to the problem of environmental pollution.

Keywords: geopolymer concrete; corncob ash, ground granulated blast furnace slag; regression model; alkaline liquids; compressive strength

1. Introduction

Portland limestone cement has been the most widely used conventional binder in the construction industry particularly, in developing countries. Presently, while the utilization of cement is reducing in the major consuming nations such as China, India, Brazil, Turkey and Russia [1], the utilization of cement in Nigeria is increasing with 31.25 million metric tons per annum (MMTPA) and a total equipped production quantity of 45 MMTPA [2] compared with the annual utilization of 19.5 million metric tons in 2009[3]. Consequently, there has been an increase in ecological imbalance as a result of Portland limestone cement production. The production of Portland limestone cement emanates carbon dioxide (CO₂) and other greenhouse gases. In 2002, *Malhotra* reported that one ton of Portland cement production emits of a ton of CO₂, and also, contributes 7% of the total greenhouse gas emissions to the earth's atmosphere [4].

In 2017, the *United Nations Statistics Division Sustainable Development Goals* reported that in 2014, 9 in 10 residing in urban areas breathed air which did not conform to World Health Organizations air quality guidelines as a result of greenhouse gases and CO₂ to the atmosphere [5]. These greenhouse gases lead to increase in global warming; increase in environmental damage; increase in respiratory diseases such as asthma and pulmonary ossification, lung cancer; kidney failure and other serious diseases to humans [6]. Therefore, safety, inclusiveness, resilience, and sustainability of cities and human settlements depend on the alternative utilization of Portland limestone cement in the production of conventional concrete in the construction industry [5] [7]. One of these alternatives is geopolymer concrete which does not use any Portland limestone cement in its production process and the materials are pozzolanic which are supplementary cementitious materials and they include ggbfs, cca, metakaolin, and fly ash [8-12]. Comparing with Portland cement production, *Davidovits* stated that there is 70-80% less CO₂ emission and 43-59% less energy required in the production of geopolymer cement (slag byproduct) [13]. Geopolymer concrete is an eco-friendly, emerging and innovative binder produced by a polymeric reaction of silica and alumina present in the source materials inducing or activating by alkaline liquids to dissolve and form a geopolymeric gel or paste.



In 2017, the *United States Department of Agriculture* reported that Nigeria alone produced 7.20 million metric tons of corn in 2016/2017 calendar year [14]. Similarly, crude steel production in Nigeria was 0.3 million tons in 2016 while the consumption is above 20 million per annum [15]. It is obviously known that these industrial and agricultural products are treated as waste products. The global output of blast furnace slag in 2014 based on the production level of crude iron and steel was estimated to be 300 million metric tons – 350 million metric tons [16]. GGBFS is a by-product of steel and iron production and during the process, slag is formed, dried and ground.

Therefore, this study is significant because it removes high elevated temperature curing regime of fresh geopolymer concrete which is not economical and practicable in the construction field. The utilization of both GGBFS and CCA as source materials allows the fresh GPC to be cured at ambient conditions. Sodium silicate gel and sodium hydroxide solution were utilized as alkaline liquids. And the ratio of sodium silicate-to-sodium hydroxide solutions was chosen as 2.5 based on the relevant studies [9] [17]. The 14 molar concentrations were adopted because higher molar concentrations result in higher mechanical strength performance [17] [18]. In addition, percentage replacement levels were selected based on the applicable studies that replacement of cement with CCA at 20-30% is feasible with compressive strengths for structural applications [19-22]. Furthermore, weaknesses in the design of GPC mix design were removed because density and aggregates are normally assumed without considering the water absorption capacity, specific gravities, and the moisture contents of materials used.

2. Materials and Methods

2.1. Materials

Dangote 3X Portland limestone cement Grade 42.5R and aggregates were used and sourced from dealers in Ota, Nigeria. Russian made sodium hydroxide (NaOH) pellets with 99% purity, sodium silicate (Na_2SiO_3) gel, and the naphthalene-based superplasticizer (Conplast- SP 430) were also used and obtained from chemical dealers in Lagos, Nigeria. Water from laboratory source was used. Corncobs were got in Agbonle, Oyo State, Nigeria. And burnt by an open burning method in order to replicate the local production. The ash was then dried, ground, and sieved with BS sieve 90 μm . GGBFS was obtained from Dolphin Steel (Nigeria) Limited, Papalanto, Nigeria. It was dried, ground, and sieved with BS sieve 90 μm . The chemical compositions of both GGBFS and CCA were analyzed using X-Ray Fluorescence (XRF) at Sagamu plant of Lafarge Holcim Plc., Nigeria. The results of chemical compositions are presented in Table 1.

Table 1 Chemical compositions of GGBFS, CCA and cement

Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Na ₂ O	M.C	LOI
GGBFS (%)	36.52	35.77	14.11	0.92	1.08	9.45	0.30	0.52	0.32
CCA (%)	12.62	60.50	11.78	9.13	1.25	1.23	0.65	1.25	0.49
Cement (%)	62.85	21.24	4.95	3.95	1.63	1.97	0.42	-	2.72

Notes: M.C (Moisture Content); LOI (Loss of Ignition)

2.2. Experimental methods

2.2.1 Design of concrete mix proportion

Both the Portland cement concrete and the geopolymer concrete mix proportions were designed in accordance with the *American Concrete Institutes* [23-24], taking into considerations, moisture contents, specific gravities, and water absorption capacities of the constituents used. Moreover, both fine aggregate (FA) and coarse aggregate (CA) were used at the saturated surface dry (SSD) conditions. The superplasticizer (Conplast SP-430) was added by 1.5% of the cementitious materials by mass. This was in accordance with the findings that 1.5% of the naphthalene-based superplasticizer by mass of the cementitious materials achieved the highest compressive strength of GPC [25-26]. The results of the volumetric computations for both PCC and GPC are presented in Table 2 and Table 3 respectively. Furthermore, PCC, 100% GGBFS + 0% CCA, 75% GGBFS + 25% CCA, 50% GGBFS + 50% CCA, 25% GGBFS + 75% CCA, and 0% GGBFS + 100% CCA were denoted as control experiment, GPC 1, GPC 2, GPC 3, GPC 4, GPC 5, and GPC 6 respectively.

Table 2 Volumetric computation of M30 PCC

S/N	Constituent	Weight (Kg/m3)	Specific Gravity	Absolute Volume (M3)	Adjusted Volume (M3)	Ratio
1	Cement	390	3.15	0.124	0.124	1.00
2	FA (SSD)	675	2.60	0.260	0.259	2.09
3	CA (SSD)	1031	2.64	0.390	0.388	3.13
4	Water	204.15	1.00	0.204	0.204	1.65
5	Air content	2.00	-	0.020	0.020	-
6	SP-430	5.85	1.20	0.005	0.005	0.04
	Total	2306		1.004	1.000	7.91

The mix ratio for PCC was 1: 2.09: 3.13

Table 3 Volumetric computation of M30 GPC

S/N	Constituent	Weight (Kg/m3)	Specific Gravity	Absolute Volume (M3)	Adjusted Volume (M3)	Ratio
1	GGBFS/CCA	390	2.90	0.134	0.142	1.00
2	FA (SSD)	675	2.60	0.260	0.276	1.94
3	CA (SSD)	1031	2.64	0.390	0.414	2.92
4	NaOH solution	60	1.49	0.040	0.042	0.30
5	Na ₂ SiO ₃ solution	150	1.60	0.094	0.100	0.70
6	Conplast SP-430	5.85	1.20	0.005	0.005	0.04
7	Air content	2.00	-	0.020	0.021	-
	Total	2306		0.943	1.000	6.90

The mix ratio for GPC was 1: 1.94: 2.92

2.2.2 Preparation of alkaline liquids

The sodium hydroxide (NaOH) solid pellet (400g) was measured and dissolved in 600g of clean water based on the 14 molar concentration. This resulted in 1000g of sodium hydroxide solution [27]. The water-to-geopolymer ratio was 0.25. This solution was prepared 24 hours prior to casting in order to cool down the exothermic reaction of the solution. Thereafter, NaOH solution was added to Na₂SiO₃ solution two hours prior to casting of concrete in order to enhance its performance for a better result.

2.2.3 Mixing and casting

The dry constituents were mixed for about four minutes. The liquid components of the mixture were then added to the dry constituents and thoroughly mixed for another four minutes. The fresh concrete was cast manually, filled in the moulds, and compacted accordingly. The fresh mix and slump test of GPC are shown in Figure 1. The slump test was carried out in accordance with the *British Standards* [28]. After 24 hours of casting, PCC specimens were demoulded and immersed in water curing tank until testing day while GPC specimens were kept in rest period for 72 hours before being demoulded to allow for proper polymerization. The curing was done at the temperature ($22 \pm 30^\circ\text{C}$) and the relative humidity ($60 \pm 5\%$).



(a) Freshly mixed GPC



(b) Slump test

Fig. 1 Fresh mix and test on the fresh concrete

2.2.4 Tests on the hardened concretes

Both the compressive strength and the density tests were carried out on the hardened concretes using a digital 2000 KN capacity compressive machine and a digital weighing balance, and the summary is presented in Table 4 while the results are shown in Figure s respectively.

Table 4 Summary of specimens' tests and curing days

Test	Specification	No of tested Samples/mix	Sample size (mm)	Curing (day)
Compressive strength	<i>British Standards</i> [29]	3 cubes	150 × 150 × 150	7 and 28
Dry density	<i>British Standards</i> [30]	3 cubes	150 × 150 × 150	7 and 28



(a) Compressive strength test



(b) Density test

Fig. 2 Tests on the hardened concrete

3. Results and Discussions

3.1. Chemical compositions of GGBFS, CCA and cement

The chemical compositions of the GGBFS used as presented in Table 1 met the requirements of *British Standards* [31] which specified that $\text{CaO} + \text{MgO} + \text{SiO}_2 \geq 66.7$; $(\text{CaO} + \text{MgO})/\text{SiO}_2 \geq 1.0$; and $\text{CaO}/\text{SiO}_2 \leq 1.4$. The SO_3 , MgO , and LOI also met the maximum requirements of 2.5%, 14.0%, and 3.0% respectively. Moreover, chemical compositions of CCA used met the requirements of *American Society for Testing and Materials C* [32] which states that $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 70\%$. Similarly, SO_3 , MgO , and LOI also satisfied the maximum requirements of 4%, 4%, and 10% respectively. In addition, chemical compositions of cement used satisfied the requirements of *British Standards* [33] which ranged the contents of SiO_2 , Al_2O_3 , Fe_2O_3 , and CaO as 18.0-24.0%, 2.6-8.0%, 1.5-7.0%, and 61.0-69.0% respectively.

3.2. Slump

Figure 3 shows the slump values for each mix proportion. The results indicate that slump value increases as the percentage replacement level of CCA increases. This is in agreement with the various findings that pozzolanic materials improve the workability of fresh concrete [34-36]. In addition, GPC extracts water from the reaction because it takes no part in the polymerization process. And during the curing process, the water is expelled from the geopolymer paste through nano-pores in the matrix [37].

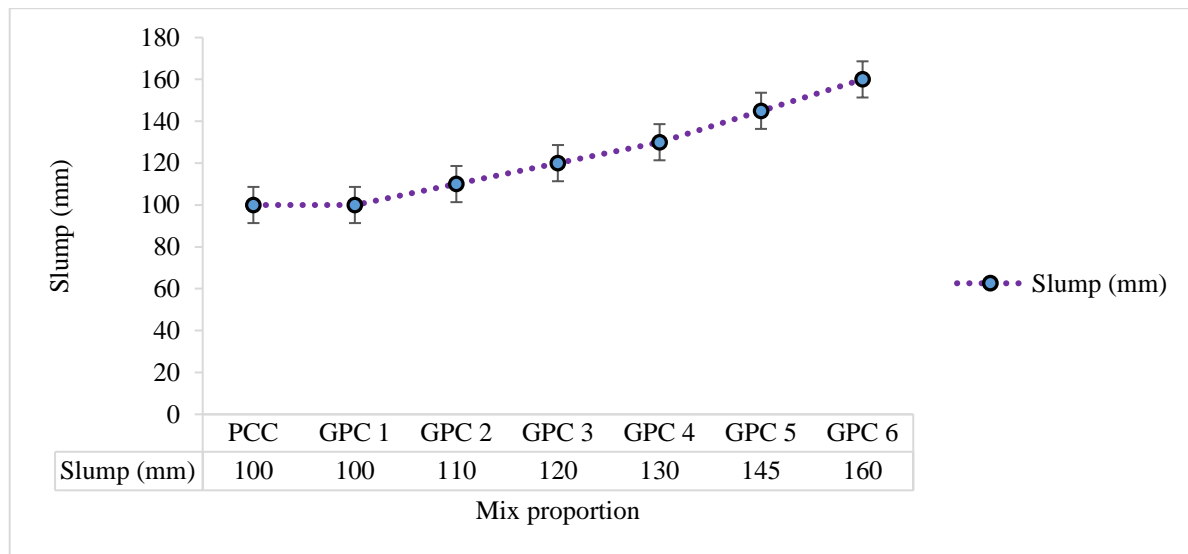
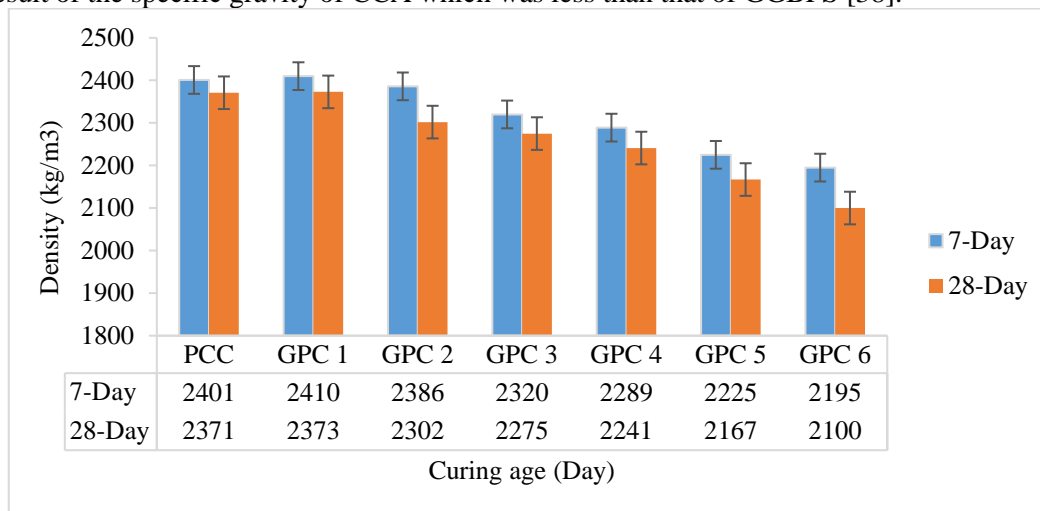


Fig. 3: Slump values (mm) for each mix proportion

3.3. Density

The density of PCC from Figure 4 ranges from 2401 kg/m³ in 7 days to 2371 kg/m³ in 28 days. The density slightly decreases with ages as a result of the hydration that takes place in the concrete. A similar pattern was noticed for GPC with a density ranging from 2410 kg/m³ in 7 days to 2100 kg/m³ in 28 days. It was observed that the addition of more CCA decreases the density in the GPC mix. This was as a result of the specific gravity of CCA which was less than that of GGBFS [38].

Fig. 4: Density (kg/m³) of PCC and GPC

3.4. Compressive strength

The comparison of the GPC with PCC at both 7 and 28 days curing from Figure 5 indicates that the compressive strength of GPC increases with CCA up to 40% replacement level and then at 60% CCA substitution, the strength decreases. Thus, 40% CCA replacement seems to be the optimal limit with compressive strength of 38.40 MPa for GPC when compared with 33.12 MPa for PCC at 28 days curing. Similarly, there is an increase in compressive strength by 22.92%, 17.96%, and 8.5% with GPC 1, GPC 2, and GPC 3 respectively when compared with the control concrete (PCC). The reactive presence of calcium-silicate-aluminate-hydrate (C-S-A-H) in the geopolymer paste and the continued-longer period of polymerization process contribute to the increase in both early and later strengths of GPC compared with PCC [39-42]. However, there is a decrease in compressive strength by 4.68%, 29.55%, and 48.31% with GPC 4, GPC 5, and GPC 6 respectively when compared with the control concrete (PCC). The decrease in compressive strength may be attributed to the reduction in the GGBFS's glassy content which reduces the CCA dissolution and retards the reaction product formation in ambient curing [37] [43-45].

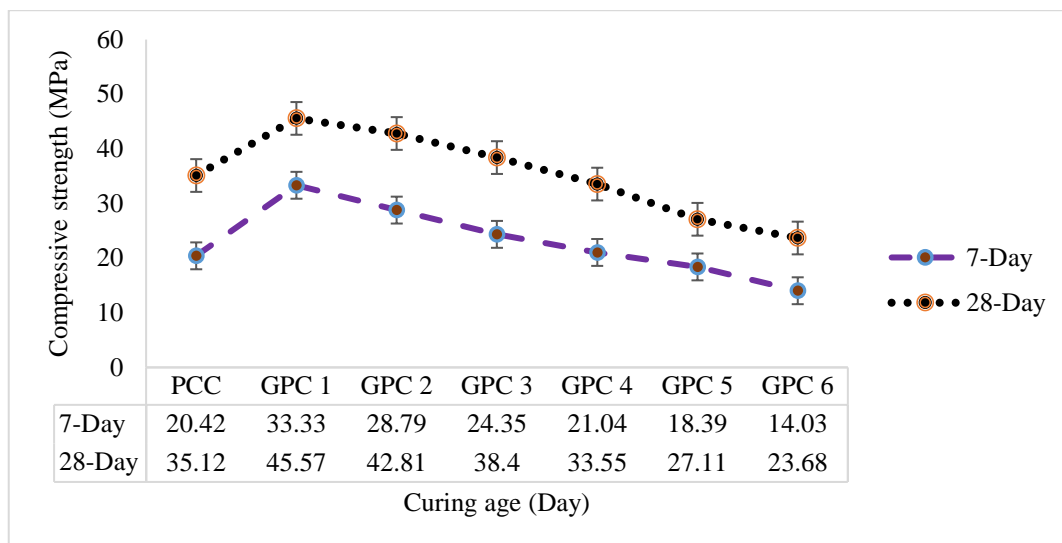


Fig. 5 Compressive strength (MPa) of PCC and GPC

3.5. Relationship between the compressive strength and the density of the GPC

Minitab 17 was used to examine the relationship that occurs between the compressive strength and the density of the GPC. Quadratic regression model of fitted line plot was engaged. And the results of regression equations at the end of 7 and 28 days curing are presented in Figure 6 and Figure 7 respectively. The coefficients of determination (R^2) based on the compressive strengths are 97.6% and 96.7% for density at 7 and 28 days respectively. These indicate that the models are 97.6% and 96.7% significantly fit to predict the relationship. And the model equations can be 95% confident that the actual values of the compressive strength will fall within the predicted values of density at 95% confidence levels. Moreover, the sequence analysis of variance tables for these models indicate that F is 0.57 and P is 0.507 while F is 0.01 and P is 0.914 for both 7 and 28 days relationships respectively. Based on the level of significance (α) of 0.05, it is revealed that P -values $> \alpha$. Thus, it is deduced that density has no zero coefficient. The ratio of variation in the response variable explained by the equation to variation left unexplained is referred to as F while P -value denotes a probability that the samples of the property data would have been obtained if the regression coefficients were all equal to zero.

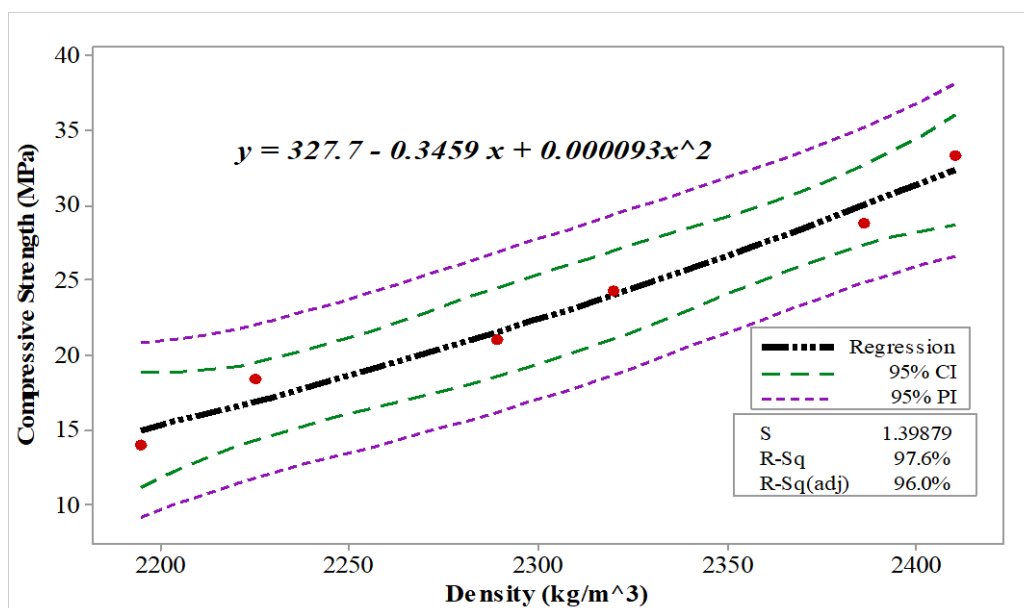


Fig.6: Relationship between the compressive strength and the density at 7 days

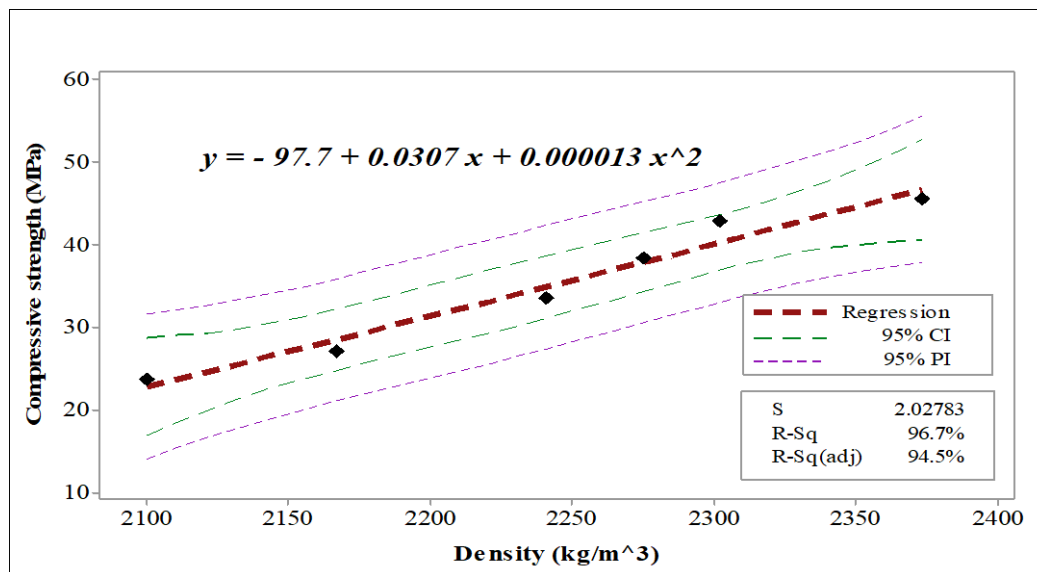


Fig.7: Relationship between the compressive strength and the density at 28 days

4. Conclusion

Geopolymer concrete shows a higher compressive strength when compared with the Portland cement concrete. Comparing with the PCC, the optimal replacement level of both GGBFS and CCA for optimum strength is obtained at 60% and 40% respectively. GGBFS and CCA-based GPC shows an emerging sustainability in place of PCC which can be utilized in general construction as a structural and non-load bearing concretes. Therefore, it is of great realistic importance to state that this study contributed to the engineering and emerging innovation for a sustainability world. It utilized the chemistry of materials for sustainable buildings, cities, and communities. Also, it established model equations to predict the compressive strength with respect to the density of the concrete.

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References

- [1] International Energy Agency- Energy Technology Systems Anal Programme (IEA- ETSAP). Cement production. IEA ETSAP - Technology brief 103: Energy Technology Systems Anal Programme, June 2010. Retrieved 25 March 2018 from www.etsap.org.
- [2] Cement Manufacturer Association of Nigeria. Gas shortage cut cement manufacturers output capacity by 36%, 2017.
- [3] Franklin A. Nigeria: Minister's forecasts 2013 self-sufficiency in cement production. Vanguard Newspaper, Nigeria, 2009, 26th November: 23.
- [4] Malhotra V M. Introduction: Sustainable Development and Concrete technology, ACI Concrete Journal, 2002: 1147-1165.
- [5] The United Nations Statistics Division Sustainable Development Goals. The sustainable development goals report. United Nations publication issued by the Department of Economic and Social Affairs (DESA), New York, NY, 2017:10017.
- [6] United Nations Environment Programme. The emissions gap report 2016. United Nations Environment Programme (UNEP), Nairobi, 2016. ISBN: 978-92-807-3617-5.
- [7] Ede A N, Adebayo S O, Ugwu E I, Emenike C P. Life cycle assessment of environmental impacts of using concrete or timber to construct a duplex residential building. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 2014, 11(2): 67-72.

- [8] Akinwumi I I, Aidomojie O I. Effect of corncob ash on the geotechnical properties of lateritic soil stabilized with Portland cement. *International Journal of Geomatics and Geosciences*, 2015, 5(3): 375-392.
- [9] Hardjito D, Rangan B V. Development and properties of low-calcium fly ash-based geopolymer concrete Research Report GC 1, Faculty of Engineering, Curtin University of Technology, Perth, Australia, 2005.
- [10] Oyeibisi S O, Olutoge F A, Ofuyatan M O, Abioye A A. Effect of corncob ash blended cement on the properties of lateritic interlocking blocks. *Progress in Industrial Ecology-An International Journal*, 2017, 11(4): 373-387.
- [11] Oyeibisi S O, Ede A N, Ofuyatan M O, Oluwafemi J O, Akinwumi I I. Comparative study of corncob ash –based lateritic interlocking and sandcrete hollow blocks. *International Journal of Geomate*, 2018, 15(51): 209-216.
- [12] Raheem A A, Oyeibisi S O, Akintayo S O, Oyeniran M O. Effects of admixtures on the properties of corncob ash cement concrete. *Leonardo Electronic Journal of Practices and Technologies*, 2010, 16: 13-20. ISSN 1583-1078.
- [13] Davidovits J. Geopolymer cement: A review. [Online], 2013. Available at <http://www.geopolymer.org/library/technical-papers/21-geopolymer-cement-review2013>
- [14] United States Department of Agriculture. World agricultural production: Circular series WAP 08-17, office of global analysis. International Production Assessment Division. South Building: Washington DC, 2017.
- [15] Iron and Steel Senior Staff Association of Nigeria. Nigeria's steel sector gets \$100m Chinese investment. *The Vanguard*, 9 November 2017 from <https://www.vanguardngr.com/2016/12/nigerias-steel-sector-gets-100m-Chinese>
- [16] Hendrik G V O. Mineral Resource of the Month: Iron and Steel Slag. *EARTH Magazine*, 3 February 2018. Retrieved 5 March 2018 from <https://www.earthmagazine.org/article/mineral-resource-month-iron-and-steel-slag>
- [17] Zarina Y, Mohd Mustafa A A, Kamarudin H, Khairul N I, Rafiza A, Andrei V S. Effect of solids-to-liquids, Na₂SiO₃-To-NaOH and curing temperature on the palm oil boiler ash (Si + Ca) geopolymerisation system. *Materials Journal*, 2015, 8: 2227-2242.
- [18] Rangan B V. Low-calcium fly ash-based geopolymer concrete. *Concrete Construction Engineering Handbook* (Chapter 26), Second Edition, New York: CRC Press, 2008.
- [19] Abdul-Manan D. Exploring the potential of alternative pozzolana cement for the northern savannah ecological zone in Ghana. *American Journal of Civil Engineering*, 2016,4(30): 74-79.
- [20] Kamaul J, Ahmed A, Hirst P, Kangwa J. Suitability of corncob ash as a supplementary cementitious material. *International Journal of Materials Science and Engineering*, 2016, 4(4): 215-228.
- [21] Oluborode K D, Olofintuyi I O. Strength evaluation of corn cob ash in a blended Portland cement. *International Journal of Engineering and Innovative Technology (IJEIT)*, 2015b, 4(12): 14-17.
- [22] Price A, Yeargin R, Fini E, Abu-Lebdeh T. Investigating effects of the introduction of corncob ash into Portland cements concrete: Mechanical and Thermal Properties. *American Journal of Engineering and Applied Science*, 2014, 7: 133-144.
- [23] American Concrete Institute 211. 1. Standard practices for selecting proportions for normal, heavyweight and mass concrete. American Concrete Institute Committee, Detroit, Michigan, 2002.
- [24] American concrete Institute 214R. Guide to evaluation of strength test results of concrete. American concrete Institute Committee, Farmington Hills, Michigan, 2011.
- [25] Malathy R. Fresh and hardened properties of geopolymer concrete and mortar. Kongu Engg. College, Perundurai. India, 2009. Retrieved November 5, 2017, from www.schleibinger.com/cmsimple/?download=r2009_malathy_geopolymer.pdf
- [26] Triwulan P W, Januarti J E. Addition of superplasticizer on geopolymer concrete. *Asian Research Publishing Network Journal of Engineering and Applied Sciences*, 2016, 11(24): 14456-14462.

- [27] Rajamane N P, Jeyalakshmi R. Quantities of sodium hydroxide solids and water to prepare sodium hydroxide solution of given molarity for geopolymer concrete mixes. Indian Concrete Institute Technical Paper, SRM University, India, 2014.
- [28] British Standard EN 12350-2. Testing fresh concrete: Method for determination of slump. British Standard Institution, 2 Park Street, London, 2009.
- [29] British Standard EN 12390 -3. Testing hardened concrete: Compressive strength of test specimens. British Standard Institution, 2 Park Street, London, 2000.
- [30] British Standard EN 12390 -7. Testing hardened concrete: Density of hardened concrete. British Standard Institution, 2 Park Street, London, 2000.
- [31] British Standard 6699. Specification for ground granulated blast furnace slag for use with Portland cement. British Standard Institution, 2 Park Street, London, 1992.
- [32] American Society for Testing and Materials C 618. Standard specification for coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete. Annual book of ASTM standards: Philadelphia, PA, 2005.
- [33] BS EN 196 – 2. Methods of testing cement – Part 2: Chemical analysis of cement. British Standard Institution (BSI), London, 1995.
- [34] Deb P S, Nath P, Sarker P K. The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials and Design*, 2014, 62: 32-39.
- [35] Nath P, Sarker P K. Effect of GGBS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Construction Building Materials*, 2014, 66: 163-171.
- [36] Provis J, Deventer JV. Alkali-activated materials: State-of-the-art report, RILEM TC 224-AAM Springe Netherlands, 2014.
- [37] Davidovits J. Chemistry of geopolymeric systems, terminology. *Proceedings of the 2nd International Conference on Geopolymer*, Saint Quentin, 1999: 9-39.
- [38] Rajini B, Narasimha Rao A V. Mechanical properties of geopolymer concrete with fly ash and ggbs as source materials. *International Journal of Innovative Research in Science, Engineering and Technology*, 2014, 3(9): 15944-15953.
- [39] Diaz E I, Allouche E N, Eklund S. Factors affecting the suitability of fly ash as source material for geopolymers. *Fuel*, 2010, 89 (5): 992–996.
- [40] Hou D, Li Z, Zhao T. Reactive force field simulation on polymerization and hydrolytic reactions in calcium aluminate silicate hydrate (C-A-S-H) gel: structure, dynamics and mechanical properties. *RSC Adv.* 2015, 5 (1): 448–461.
- [41] Oh J E, Monteiro P J M, Jun S S, Choi S, Clark S M. The evolution of strength and crystalline phases of alkali-activated ground blast furnace slag and fly ash-based geopolymers. *Cement Concrete Resources*, 2010, 40 (2): 189-196.
- [42] Temuujin J, Williams R, Van Riessen A. Effect of mechanical activation of fly ash on the properties of geopolymer cured at ambient temperature. *Journal of Materials Processing Technology*, 2009, 209 (12): 82-88.
- [43] Palomo A, Grutzeck M W, Blanco M T. Alkali-activated fly ashes: A Cement for the future. *Cement and Concrete Research*, 1999. 29 (8): 1323-1329.
- [44] Puligilla S, Mondal P. Role of slag in microstructural development and hardening of fly ash-slag geopolymer. *Cement and Concrete Research*, 2013, 43: 70–80.
- [45] Xu H, Deventer J V. The geopolymerization of alumino-silicate minerals. *International Journal of Mineral Processing*, 2000, 59(3): 247-266.